Metalation of Carbaporphyrinoid Systems

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Diverse carbaporphyrinoid systems have been synthesized using '3 + 1' MacDonald condensations, Lindsey-Rothemund reactions and other strategies. In common with the N-confused porphyrins (NCPs), these compounds have a CNNN core that can facilitate the generation of organometallic derivatives. Benzocarbaporphyrins and tropiporphyrins, with indene or cycloheptatriene units in place of a pyrrole ring, readily form silver(III) complexes and some gold(III) derivatives have also been prepared. On the other hand, benziporphyrins and azuliporphyrins, which have a benzene or azulene unit in place of a pyrrole moiety, are dianionic ligands that afford Ni^{II}, Pd^{II} and Pt^{II} complexes. Stable iridium and rhodium derivatives of azuliporphyrins can also be generated. 2-Methyl or 2-phenyl NCPs act as dianionic ligands forming Ni^{II} and Pd^{II} complexes but reactions with silver(I) acetate gave the aromatic 3-oxoNCP silver(III) derivatives. A related N-phenylpyrazole-containing porphyrinoid gave nickel(II) and palladium(II) complexes but these showed little or no aromatic character. Oxybenziporphyrins, which have a semiquinone subunit, can form Pd^{II}, Pt^{II}, Cu^{III}, Ag^{III} and Au^{III} derivatives and can therefore act as both dianionic and a trianionic ligands. Finally, a diazuliporphyrin has been used to prepare the first example of a palladium(II) dicarbaporphyrinoid complex. These investigations demonstrate that the unique characteristics of organometallic compounds derived from carbaporphyrins and related porphyrin analogues are starting to rival the significance of the better known metal complexes of N-confused porphyrins.

Introduction

In 1994, the first examples of N-confused porphyrins (NCPs; **1**, Figure1) were described.[1,2] These porphyrin isomers were formed as by-products in Rothemund-type syntheses from pyrrole and aromatic aldehydes, but were initially only generated in approximately 5% yield. Rational routes to *meso*-unsubstituted N-confused porphyrins were subsequently developed[3,4] using the '2 + 2' and '3 + 1' MacDonald methodologies.[5] In 1999, superior "one pot" reaction conditions were discovered by Geier *et al.* that used methanesulfonic acid as a catalyst, and this procedure gives *meso*-tetrasubstituted NCPs in up to 40% yield.[6] NCPs have attracted considerable interest due to their novel reactivity and spectroscopic properties.[7-12] The long wavelength absorptions exhibited by NCPs and related systems suggest that they may have complementary applications to true porphyrins and could potentially be used as photosensitizers in photodynamic therapy (PDT).[13] NCPs have two tautomeric forms that differ in energy by only 5 kcal/mol, and the less favorable cross-conjugated form **2** often predominates over **1** in polar aprotic solvents while the fully aromatic porphyrinoid **1** is favored in more conventional solvents such as chloroform.[14] The macro-cyclic core in NCPs has a carbon atom replacing one of the nitrogens in true porphyrins, but NCPs and related doubly N-confused porphyrins readily afford stable organometallic derivatives.[10] This aspect of NCP chemistry has been widely exploited to synthesize a wide variety of complexes involving both inner core metalation and/or coordination at the outer nitrogen. These complexes can be formally derived from both of the major tautomeric species, although the fully aromatic form is better suited to stabilize metal cations in higher oxidation states such as silver(III).[15,16]

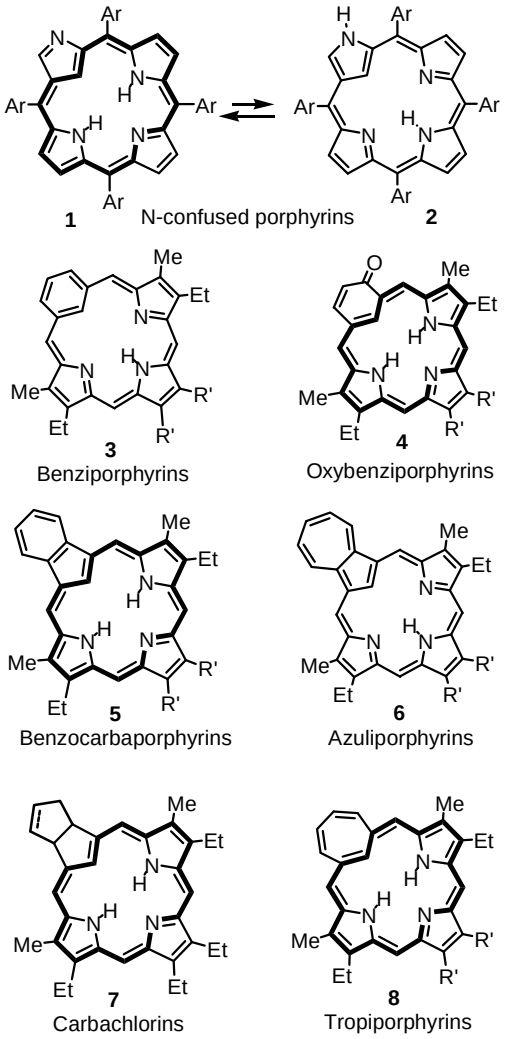

Figure 1. Selected examples of carbaporphyrinoid systems.

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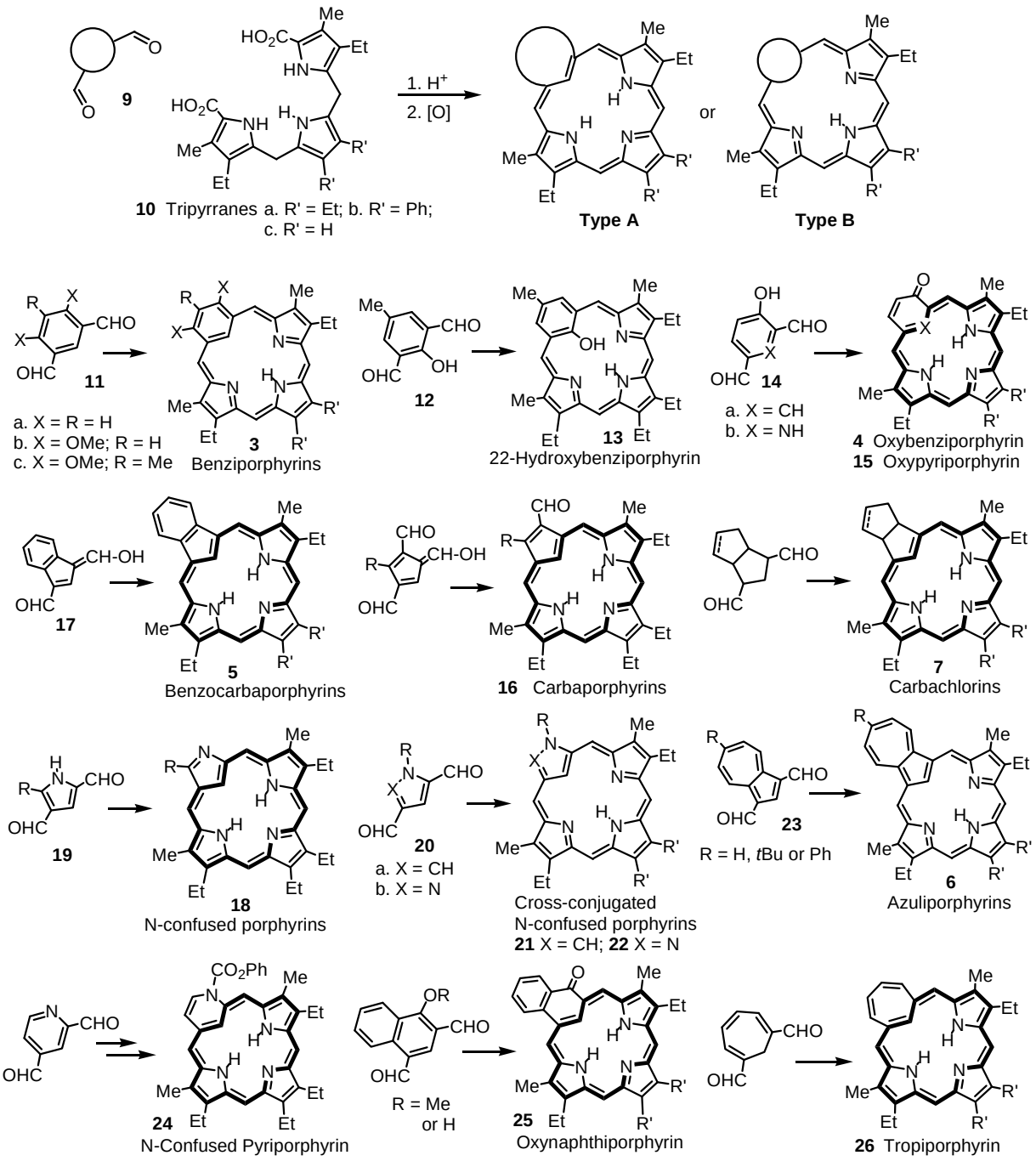
Shortly after the accidental discover of NCPs, a series of related carbaporphyrinoid systems were reported.[5,17-19] These systems share the CNNN core found in NCPs but have far greater potential for structural diversity. These variables allow for greater differences in both reactivity and spectroscopic properties, and the element of symmetry present in many of these structures also allows for a simplification in the characterization of these systems as well as facilitating greater regiochemical selectivity. Although the first synthesis of a benziporphyrin **3** (Figure 1) was reported in the same year that the earliest papers on NCPs were published,[20-22] and syntheses of oxybenziporphyrins **4**,[21,22] carbaporphyrins (*e.g.* **5**),[23,24] azuliporphyrins **6**,[25] carbachlorins **7**[26] and tropiporphyrins **8**[27] were reported over the next three years, until recently studies on these carbaporphyrinoid systems have fallen under the shadow of the NCPs. Nevertheless, a number of innovative synthetic routes have been developed for the synthesis of carbaporphyrinoids such as **3**-**8**, and these systems have been shown to be capable of generating diverse organometallic complexes. These investigations have not only complemented the work conducted on NCPs but have also lead to the discovery of a significant class of novel organometallic compounds.

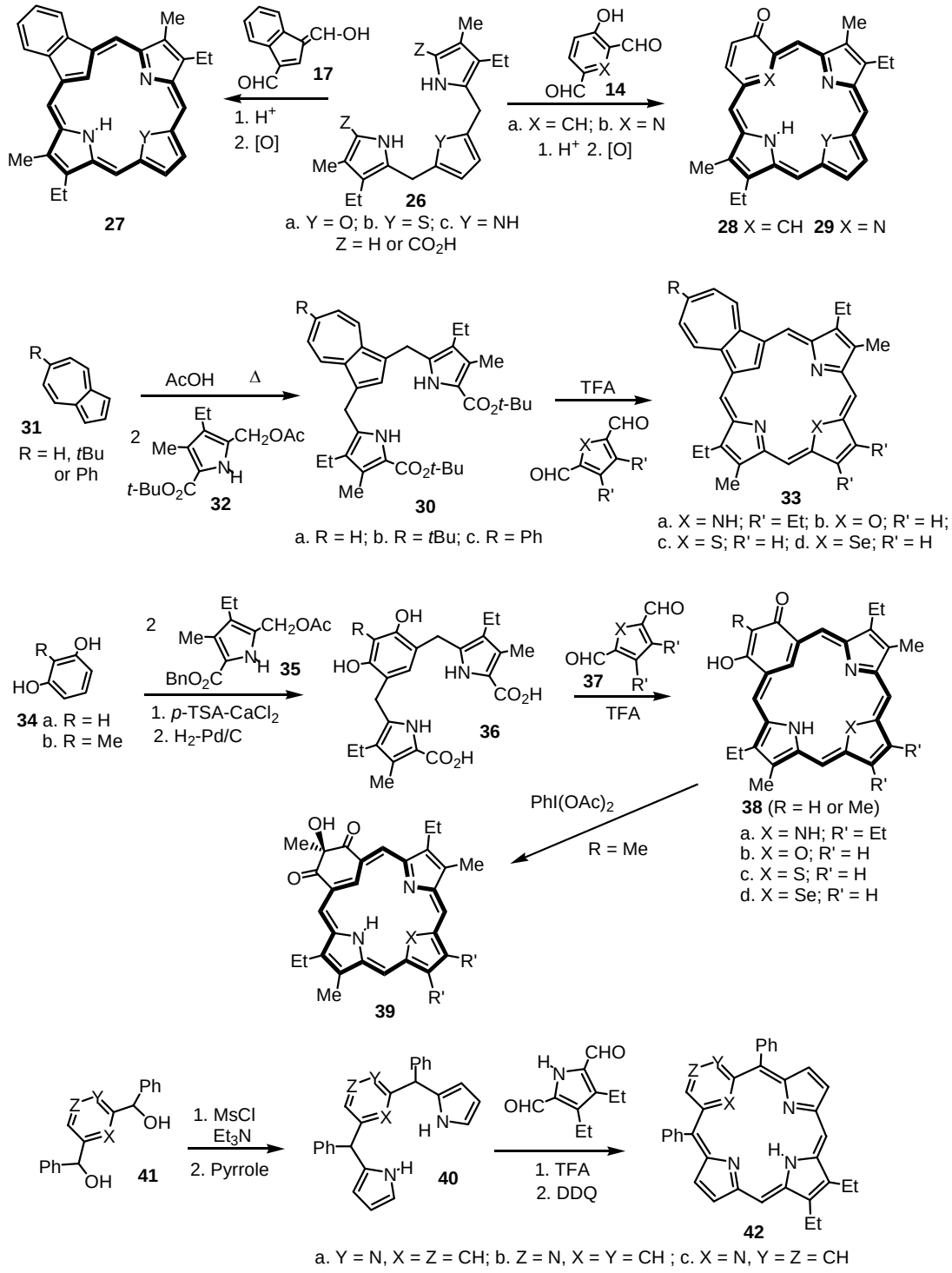
In this review, the methods available for synthesizing carbaporphyrinoid systems are discussed and recent developments on the metalation of these systems are described.



Scheme 1. Synthesis of carbaporphyrinoid systems from tripyrranes.

Synthetic Methodologies

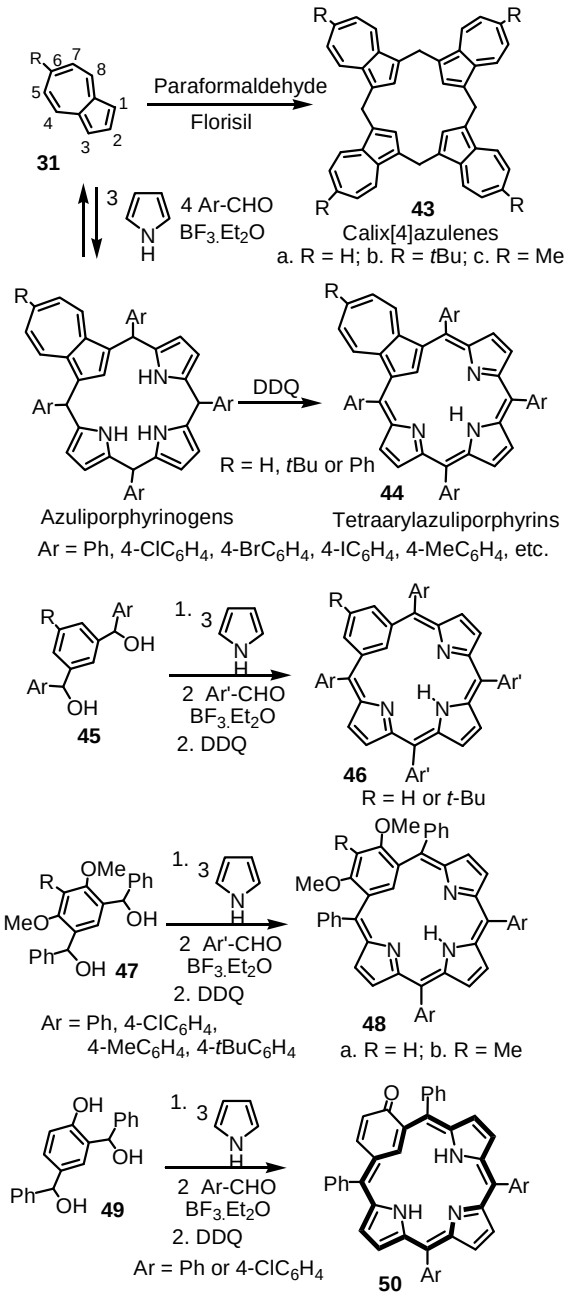
One of the most versatile methods for porphyrin synthesis is a '3 + 1' variant on the MacDonald condensation (Scheme 1).[5] In this methodology, a dialdehyde **9** is condensed with a tripyrrolic intermediate (tripyrrane **10**) in the presence of an acid catalyst.[28] Following oxidation of a dihydroporphyrinoid intermediate, the porphyrinoid system is generated.[28-31] In most cases the yields fall into a 30-50% range, although >80% yields have been noted in some cases.[28,30] When a carbocyclic dialdehyde is used, carbaporphyrinoid products of type A or type B can be formed (Scheme 1).[17-19] In type A, a porphyrin-like conjugation pathway is retained and this allows for highly diatropic structures to be generated. However, in other cases the carbocyclic unit is cross-conjugated and the macrocycle becomes less aromatic or nonaromatic. Reaction of isophthalaldehyde (**11a**) with tripyrrane **10** gives the nonaromatic benziporphyrin **3a**,[20-22] while related dimethoxybenzenedialdehydes **11b** and **11c** give dimethoxybenziporphyrins **3b** and **3c**, respectively.[32] Similarly, 2-hydroxy-5-methyl-1,3-benzenedicarbaldehyde (**12**) reacts with **10** to afford the hydroxybenziporphyrin **13**, and the internal hydroxyl substituents does not appear to



Scheme 2. Synthesis of carbaporphyrinoid systems from tripyrrane analogues.

significantly inhibit macrocycle formation.[33] In the early stages of these studies, we speculated that the presence of a 4-hydroxyl unit on the benzene moiety would facilitate a keto-enol tautomerization to give an aromatic type A porphyrinoid **4** rather than type B benziporphyrins obtained from dialdehydes **11** and **12**.[21] This proved to be the case, as reaction of **14** (X = CH) with **10** in the presence of 5% TFA in dichloromethane, followed by oxidation with DDQ, afforded the highly diatropic system oxybenziporphyrin **4**.[21,22] Oxybenziporphyrin **4** has an arrangement of core atoms than mimics tautomer **1** for NCPs, while benziporphyrins **3** more closely resemble the cross-conjugated tautomer **2**.[21,22] The same trick can be applied to the synthesis of oxypyriporphyrins **15**.[22,33,34] 3-Hydroxy-2,6-pyridinedicarbaldehyde (**14**; X = N) reacted with tripyrranes **10** under the unusual '3 + 1' conditions to give the aromatic pyridone-containing macrocycle in excellent yields.[34] Other aromatic type A systems include benzocarbaporphyrins **5**,[24,35] carbaporphyrins **16**[23,24] and carbachlorins **7**,[26] all of which can be formed by reacting the necessary dialdehyde precursors with tripyrranes **10** (Scheme 1). The use of indene dialdehyde **17** in this chemistry to generate benzocarbaporphyrins **5** has been particularly successful.[24] The same strategy was applied in the synthesis of *meso*-unsubstituted NCPs **18** from 2,4-pyrroledicarbaldehydes **19**.[36] In this work, excellent yields of NCPs could be isolated so long as ferric chloride was used as the oxidant and the products were recrystallized as the hydrochloride salts.[36] Recently, N-methyl and N-phenyl pyrrole dialdehydes **20** (X = CH) were shown to react with tripyrranes **10** to give the cross-conjugated NCPs **21**.[37] In addition, pyrazole dialdehydes **20** (X = N) reacted with **10** to give the related nonaromatic 3-aza-NCPs **22**. Although NCPs **21** showed some diatropic character, this property was not evident in the pyrazole-containing porphyrinoids **22**.[37] Azulene dialdehydes **23** react with tripyrranes **10** to give a particularly important group of porphyrin analogues known as azuliporphyrins (**6**).[25,38,39] Azuliporphyrins **6** show comparable diatropic character to the cross-conjugated NCPs **21**, in both cases showing the internal CH resonances in proton NMR spectra near 3 ppm, although this property is greatly enhanced upon protonation.[25,39] Other systems that have been prepared using the '3 + 1' approach include N-confused pyriporphyrin **24**,[40] oxynaphthiporphyrins **25**[41] and tropiporphyrins **8**.[27,42]

Further structural diversity can be introduced when modified tripyrrane structures are utilized in these syntheses (Scheme 2). Hence, when furan and thiophene tripyrrane analogues **26** were reacted with indene dialdehyde **17**, the corresponding 23-oxacarbaporphyrins **27a** and thiacarbaporphyrins **27b** could be generated.[43,44] In addition, similar heteroanalogues of oxybenziporphyrins (**28**) and oxypyriporphyrins (**29**) could also be easily formed.[43,44] Azulene undergoes electrophilic substitution at the 1 and 3 positions, and this allows the formation of azulitripyrranes **30** when azulenes **31** are reacted with two equivalents of an acetoxymethylpyrrole **32** in the presence of acetic acid.[39,45,46] These tripyrrane analogues were generated with terminal *tert*-butyl ester protective groups. Following deprotection with TFA, the azulitripyrranes were condensed with pyrrole, furan, thiophene or selenophene dialdehydes to give azuliporphyrins and their heteroanalogues **33** in good yields.[39,46] Resorcinol (**34a**) and 2-methylresorcinol (**34b**) were also shown to react with acetoxymethylpyrroles **35** in the presence of *p*-toluenesulfonic acid and calcium chloride to give tripyrrane analogues with terminal benzyl ester protective groups.[47] Following hydrogenolysis over 10% palladium-charcoal, the related dicarboxylic acids **36** were reacted with dialdehydes **37** (X = NH, O, S or Se) to give a series of rather insoluble hydroxyoxybenziporphyrins **38**.[47] The macrocyclic products derived from methylresorcinol (R = Me) underwent further oxidation with $PhI(OCOCF_3)_2$ to afford the unusual but highly aromatic 3-hydroxy-2,4-diones **39**.[47] Pyritripyrranes **40** were also prepared from pyridine dicarbinols **41** and these reacted with pyrrole dialdehydes to give a series of pyriporphyrins **42**.[40] In **42b** and **42c**, a carbon atom is present in the macrocyclic core and these systems can be considered to be azabenziporphyrins.[40]



Scheme 3. Rothemund-type syntheses of carbaporphyrinoids.

More direct routes to carbaporphyrinoid systems have also been developed (Scheme 3). Azulene favors electrophilic substitution at the 1 and 3 positions that are structurally analogous to the α-positions in pyrroles. As pyrroles cyclotetramerize to give calix[4]pyrroles or porphyrins, the possibility of generating calix[4]azulenes **43** from the reaction of azulenes **31** with paraformaldehyde was investigated.[48] Although many acid catalysts afforded low yields of **43**, the macrocyclic product could not be purified by column chromatography. After attempting this reaction under numerous conditions, florisil was found to be an excellent catalyst and **43** was isolated in >70% yield.[48] The synthesis of **43** resembles a Rothemund-type porphyrin synthesis,[49] and this lead us to speculate that the same approach might be used to prepare azuliporphyrins **44**.[50] Using conditions adapted from Lindsey's methods for preparing tetraaryl-porphyrins,[51,52] a 1:3:4 molar ratio of azulene, pyrrole and arylaldehydes were stirred with $BF_3{\cdot}Et_2O$ in chloroform for 16 hours. Following oxidation with DDQ and column chromatography, the tetraarylazuliporphyrins **44** were isolated in good yields (generally 10-20%).[50,53,54]

A similar approach to benziporphyrins was also reported.[55] Benzene dicarbinols **45** were reacted with pyrrole and aromatic aldehydes using catalytic $BF_3{\cdot}Et_2O$ in dichloromethane to give, following oxidation with DDQ, the tetraarylbenziporphyrins **46**.[55] We have recently developed improved methods for the synthesis of dicarbinols **45** and this allows the introduction of novel substitution patterns on the benziporphyrin core.[56] Dimethoxybenzenedicarbinols **47** were easily prepared by reacting dilithio-derivatives with benzaldehyde and these also reacted with pyrrole in the presence of $BF_3{\cdot}Et_2O$ to give the dimethoxybenziporphyrins **52**.[57,58] Despite the high degree of the steric congestion in **52** due to the presence of the *meso*-substituents, these benziporphyrins still show some diatropic character. In the proton NMR spectrum of **48a**, the internal CH is shifted upfield to 5.8 ppm (Figure 2*A*). Although this shift is small, the chemical shift for this resonance is consistent with a degree of aromatic character being present in these benziporphyrins that results from the electron-donating effects of the methoxy substituents.[57,58] In the presence of TFA, the aromatic character of **48a** is greatly increased as the protonated benziporphyrin shows this resonance further shifted upfield to 3.3 ppm (Figure 2*B*).[58] Even though a dication is generated, the NH resonances are still shifted upfield compared to the free base. Nevertheless, these shifts are relatively small compared to the oxybenziporphyrins.[21] However, this aromatic carbaporphyrinoid system can also be obtained by reacting the phenolic dicarbinol **49** with pyrrole and aromatic aldehydes under the Lindsey-Rothemund conditions.[59] Although the *meso*-tetraaryl oxybenziporphyrins **50** show smaller upfield shifts than the *meso*-unsubstituted oxybenziporphyrins, the internal CH is still observed upfield near -3 ppm.[59]

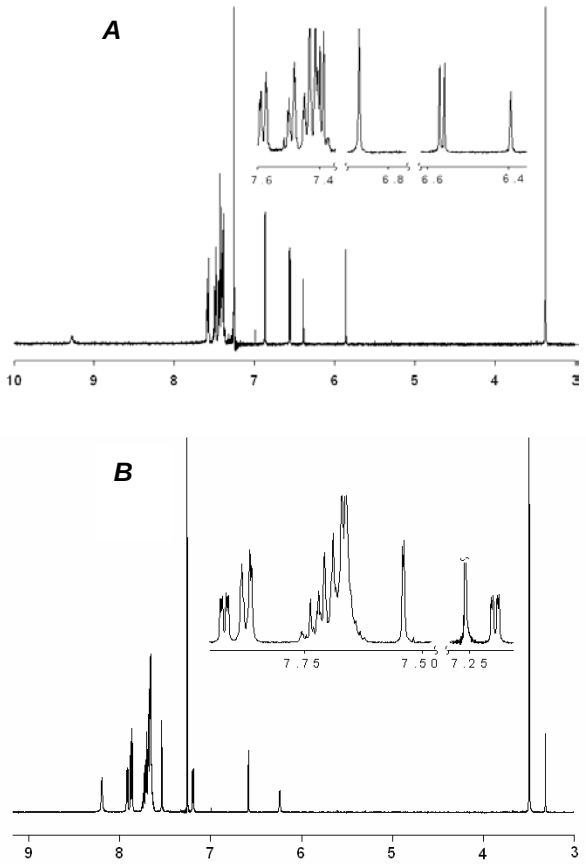
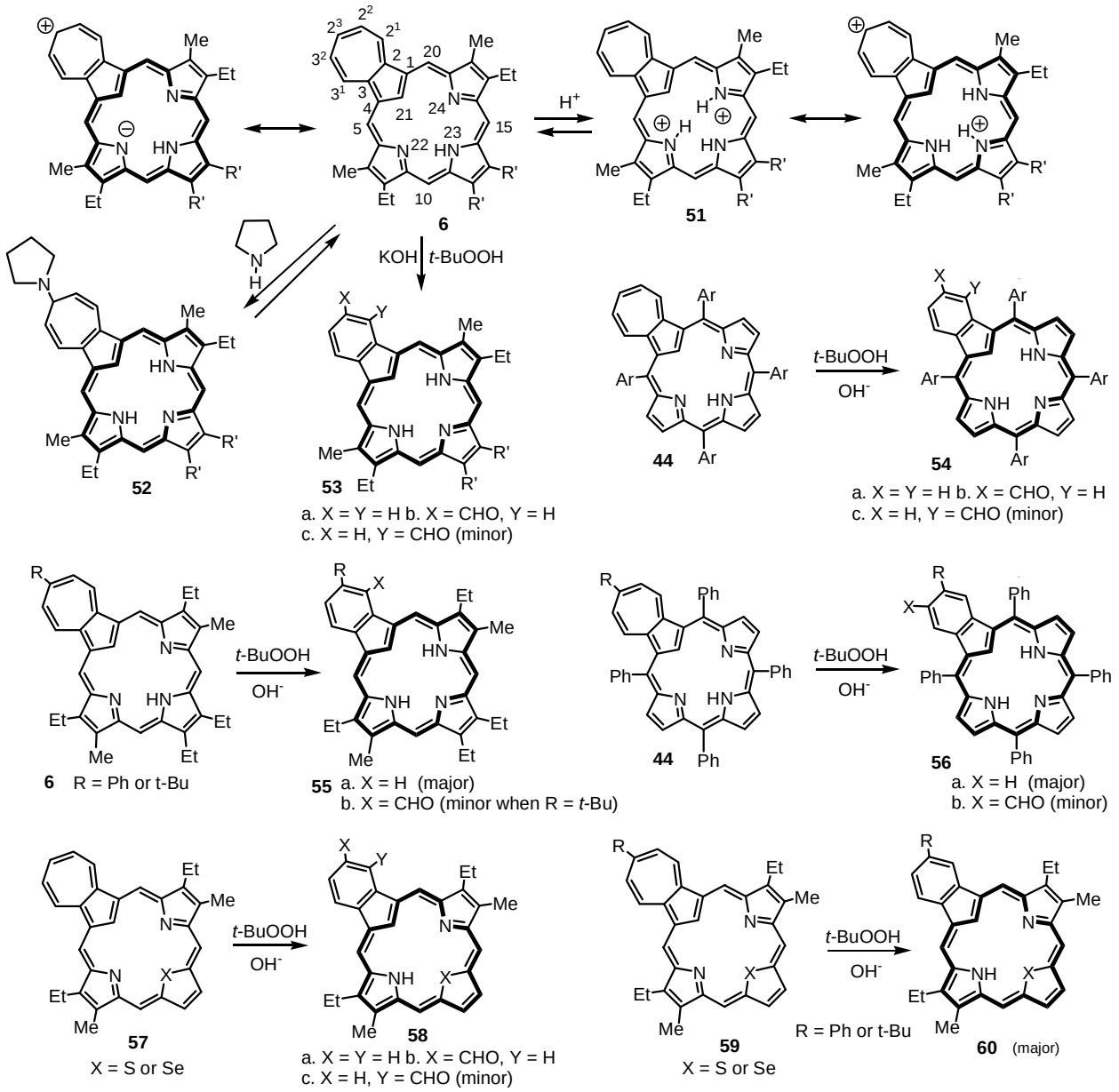


Figure 2. 400 MHz proton NMR spectra of dimethoxybenziporphyrin **48a** showing the presence of significant diatropic character despite the cross-conjugated nature of the benzene subunit. *A* - Free base in $CDCl_3$. *B* - Dication in TFA-$CDCl_3$. In the latter spectrum the internal CH shifts upfield to 3.3 ppm.

Benzocarbaporphyrins can also be derived from azuliporphyrins **6** (Scheme 4).[38] Azuliporphyrins are relatively polar systems that derive borderline aromatic properties from dipolar canonical forms that simultaneously give the structure carbaporphyrin and tropylium aromatic characteristics.[25] This character is limited due to the associated requirement for charge separation. However, protonation gives a dication **51** where the tropylium resonance contributor takes on greater significance because it now facilitates charge delocalization.[25] Nevertheless, the seven-membered ring of the free base azuliporphyrins is susceptible to nucleophilic attack due to its tropylium-like characteristics.[38] In the presence of nucleophiles like pyrrolidine, adducts **52** may be generated that take on fully aromatic carbaporphyrin-type spectroscopic properties.[38,39] Azuliporphyrins **6** can undergo oxidative ring contractions to afford benzocarbaporphyrins **53**, and this chemistry readily occurs in the presence of *tert*-butyl hydroperoxide and potassium hydroxide.[38,39] Although mixtures of several carbaporphyrin products may be generated, this chemistry provides an alternative route to benzocarbaporphyrins.[38,39] Tetraarylazuliporphyrins **44** similarly react with ^{t}BuOOH and KOH to give the analogous benzocarbaporphyrins **54**, and it is noteworthy that this is currently the only known route to tetraaryl benzocarbaporphyrins.[50,53] In the tetraaryl benzocarba-porphyrin series **54**, the signal of the inner CH is still shifted upfield to beyond –5 ppm and the UV-vis spectra are porphyrin-like showing the presence of a strong Soret band and several *Q* absorptions.[50,53] However, X-ray crystallography shows that the indene unit is significantly tilted from the mean plane of the macrocycle



Scheme 4. Synthesis of benzocarbaporphyrins from azuliporphyrins.

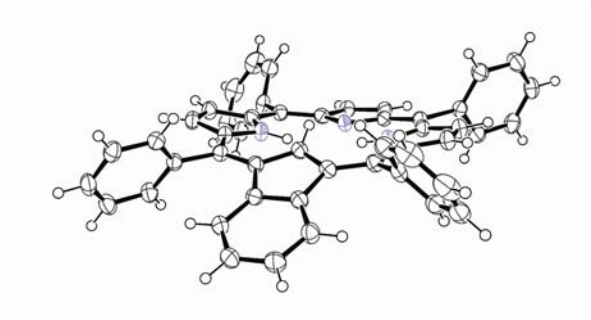
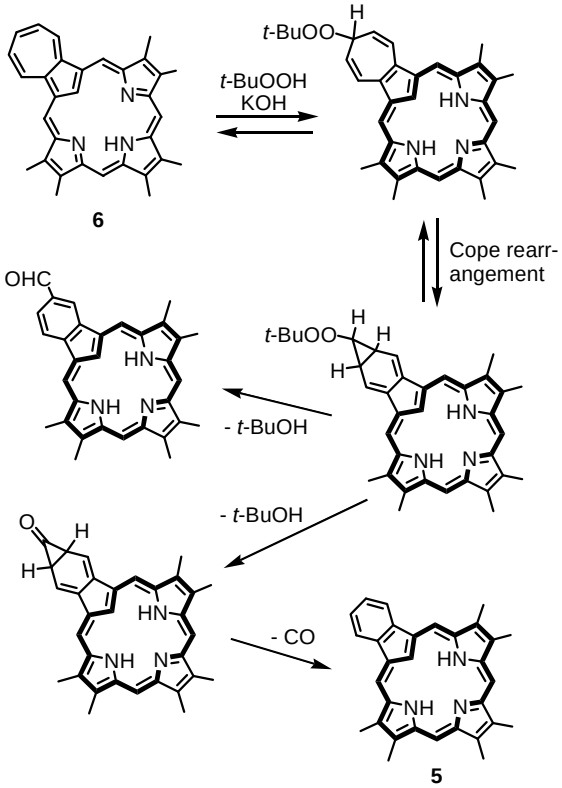


Figure 3. X-ray crystal structure of tetraphenylbenzocarbaporphyrin **54**.[53]

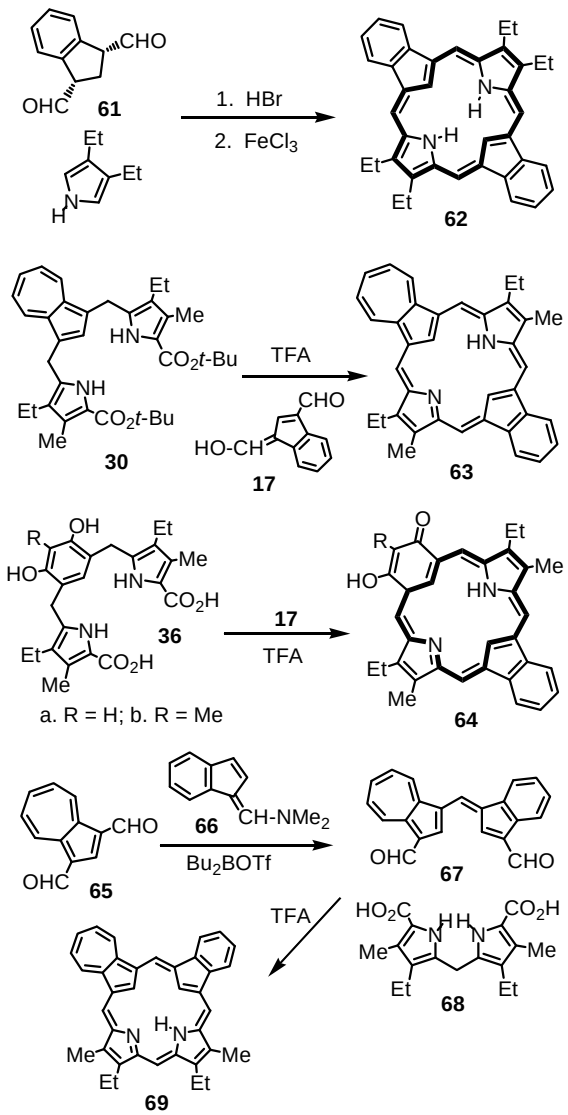
(Figure 3), in part due to the presence of two flanking phenyl substituents.[53] The ring contractions are believed to be triggered by an initial nucleophilic attack from the *tert*-butyl hydroperoxide anion at position 2^3 of azuliporphyrin **6** (Scheme 5).[38] Following a Cope rearrangement, elimination of *tert*-butyl alcohol would give a benzocarbaporphyrin aldehyde or a fused cyclopropanone that can extrude CO to give the benzoporphyrin **5** lacking a formyl moiety.[38,53] Attack at position 2^2 could give rise to an alternative aldehyde product.[38,53] Surprisingly, azuliporphyrins **6** with phenyl or *tert*-butyl substituents on position 2^3 also readily underwent ring contractions to benzocarbaporphyrins **55** (Scheme 4).[46] The results indicated that nucleophilic attack could still occur at positions 2^2, and to a lesser extent 2^1, and even the presence of a *tert*-butyl substituent could not block this process. Tetraphenylazuliporphyrins **44** derived from 6-phenyl or 6-*tert*-butylazulene also gave benzocarbaporphyrin products **56** upon treatment with KOH-^{t}BuOOH, although not unexpectedly these appear to arise solely from nucleophilic attack at position 2^2 of the azuliporphyrin.[54] Heteroazuliporphyrins **57** (X = S or Se) also react under these conditions to give thia- and selenacarbaporphyrins **58**,[39] and the related heteroazuliporphyrins **59** with

2^3-phenyl or *tert*-butyl substituents similarly afforded heterobenzocarbaporphyrin products **60**.[60]



Scheme 5. Mechanism for the peroxide induced ring contraction of azuliporphyrins to give benzocarbaporphyrins.

Syntheses of dicarbaporphyrins and related macrocycles are less advanced, but several routes to these systems have now been reported (Scheme 6). Indane dialdehyde **61** was reported to react with diethylpyrrole in the presence of HBr, followed by oxidation with ferric chloride, to give the *opp*-dicarbaporphyrin **62**.[61] This dicarbaporphyrin is very aromatic based upon the strongly diatropic ring current observed by proton NMR spectroscopy, and has a porphyrin-like UV-vis spectrum. However, **62** is rather unstable and this has limited further investigations.[61] Azulitripyrrane **30** has been shown to react with indene dialdehyde **17** under '3 + 1' MacDonald condensation conditions to give the 23-carbaazuliporphyrin **63**.[45] Similarly, resorcinol-derived tripyrrane analogues **36** reacted with **17** to yield to the *opp*-carbaoxybenziporphyrins **64**.[62] Unfortunately, **63** is also rather unstable and dicarbaporphyrinoids **64** have poor solubility characteristics, so these systems also have only been investigated to a limited extent. Macrocycles with two adjacent carbocyclic rings have recently been shown to be far more promising for future investigations.[63] In particular, azulene-dialdehyde **65** has been shown to react with an indene enamine **66** in the presence of dibutylboron triflate to give a fulvene dialdehyde **67**. Further acid catalyzed MacDonald '2 + 2' condensation with a dipyrrylmethane dialdehyde **68** afforded the *adj*-dicarbaporphyrinoid system **69**.[61] This 22-carbaazuliporphyrin has some diatropic character, but is quite stable and is reasonably soluble in organic solvents.[61]

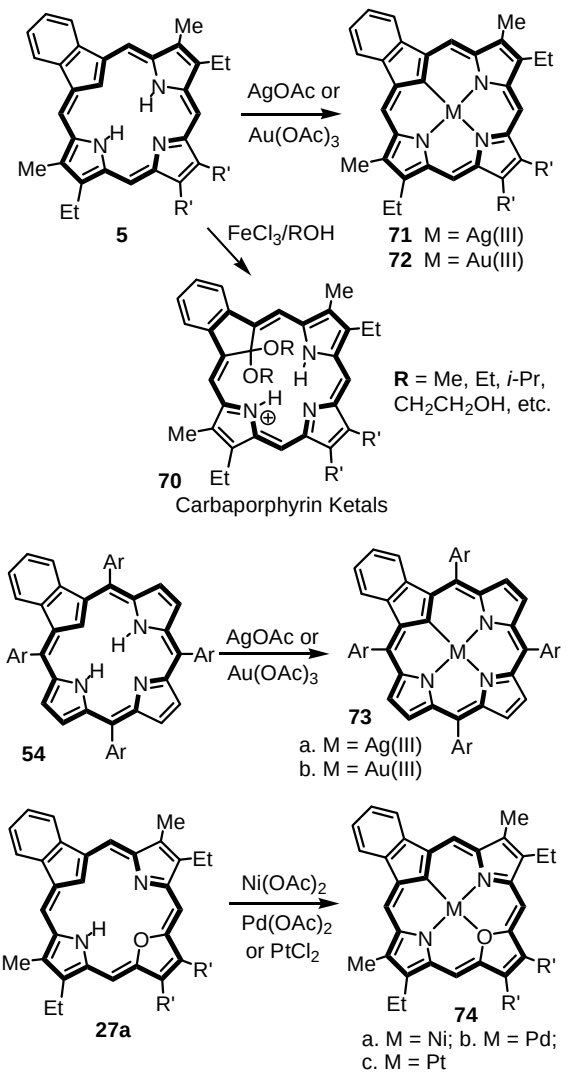


Scheme 6. Synthesis of dicarbaporphyrinoid systems.

Metalation of Carbaporphyrins and Related Macrocycles

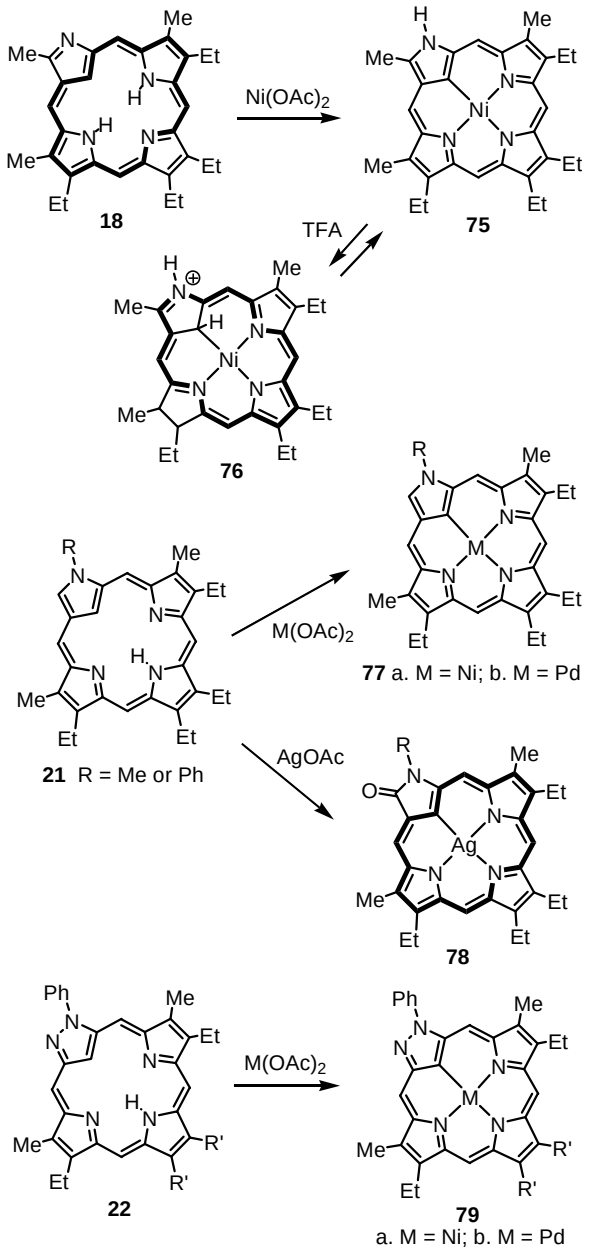
Our initial attempts to metalate benzocarbaporphyrins **5** or oxybenziporphyrins **4** with nickel(II), copper(II) or zinc salts were unsuccessful.[64] In the inital phases of these studies, benzocarbaporphyrin **5** was heated with excess ferric chloride in refluxing methanol-chloroform in an attempt to generate an iron complex (Scheme 7).[64,65] In fact, even at the time we considered these conditions to have little chance of working because it is difficult to insert Fe^{III} directly into porphyrins, but we were trying out many different reaction conditions. As it worked out, the initial brown colored solution quickly turned bright green during the reflux.[64] However, the resulting product was not a metallo-derivative. It turned out that ferric chloride efficiently oxidizes **5** at the internal carbon and generates a ketal product **70**.[64,65] This regioselective oxidation affords good yields of the polar ketal products which are isolated as hydrochloride salts. They show strong absorptions in the far red and for this reason show some potential for applications as photosensitizers in PDT.[64,65] Furthermore,

these ketals have been shown to be active against *Leishmania* and this property could lead to the development of a new treatment for leishmaniasis.[66] Subsequently, we noted that silver(I) acetate smoothly reacted with benzocarbaporphyrins **5** to give the silver(III) derivatives **71**.[41,67,68] These nonpolar derivatives are stable aromatic compounds and X-ray crystallography shows that the macrocycle is virtually planar. Reaction with gold(III) acetate gave a low yield of the gold(III) carbaporphyrin **72** but good yields of both the silver(III) and gold(III) derivatives **73** can be obtained by reacting the tetraarylbenzocarbaporphyrins **54** with silver(I) or gold(III) acetate.[68] Hence, this system is able to stabilize relatively high oxidation states of metals in common with NCPs **1**. Oxacarbaporphyrin **27**, which has two internal hydrogens, reacted with nickel(II) or palladium(II) acetate to give the nickel(II) or palladium(II) organometallic complexes **74a** and **74b** instead, and reactions with $PtCl_2$ also gave low yields of the related platinum(II) complex **74c**.[43,44]



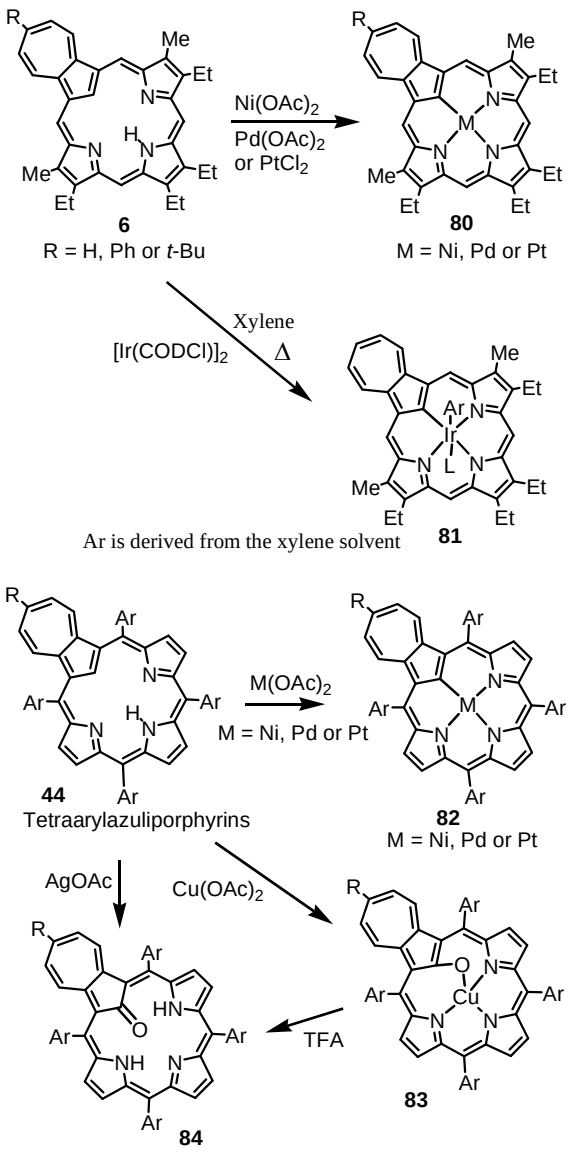
Scheme 7. Metalation of benzocarbaporphyrins.

Although the metalation of *meso*-substituted NCPs has been heavily investigated, little work has been carried out on the metalation of *meso*-unsubstituted N-confused porphyrins (Scheme 8). The heptaalkyl NCP **18** was shown to react with Ni^{II} acetate in DMF to give the moderately unstable Ni^{II} complex **75**.[36] Interestingly, if a drop of trifluoroacetic acid (TFA) is added to a solution of **75** in $CDCl_3$, the proton NMR spectrum shows the immediate formation of an aromatic C-protonated derivative **76**.[36] This protonation is reversible but if the solution is left for several hours the complex undergoes an irreversible demetalation to give protonated NCP.[36] In recent studies, the N-Me and N-Ph NCPs **21** have been shown to react with $Ni(OAc)_2$ or $Pd(OAc)_2$ to afford similar nickel(II) and palladium(II) complexes **77**.[37] C-protonation was also observed for the nickel complexes. In addition, reaction with silver(I) acetate not only metalated the carbaporphyrinoid interior, but also gave rise to an oxidation on the inverted pyrrole ring to give the keto-NCP silver(III) derivatives **78**.[37] The N-phenyl pyrazole-containing NCP **22** has also been shown to give stable nickel(II) and palladium(II) complexes **79**.[37]



Scheme 8. Metalation of *meso*-unsubstituted N-confused porphyrins.

Azuliporphyrins have been shown to be versatile organometallic ligands (Scheme 9).[69,70] Azuliporphyrins **6** react with $Ni(OAc)_2$, $Pd(OAc)_2$ or $PtCl_2$ to give the nickel(II), palladium(II) or platinum(II) complexes **80** and these have been fully characterized by NMR, UV-vis spectroscopy, MS, electrochemistry and X-ray crystallography.[69,70] In more recent investigations, **6** was shown to react with $[Ir(CODCl)]_2$ in refluxing *o*-xylene to give iridium(III) complex **81**, and preliminary results show that similar rhodium(III) complexes can also be generated.[71] Tetraarylazuliporphyrins **44** also readily form Ni^{II}, Pd^{II} and Pt^{II} complexes **82**.[70] However, reaction with copper(II) acetate gave rise to an oxidative metalation process forming the copper(II) complex **83**.[72] This system is very distorted and the X-ray crystal structure shows that the azulene subunit is tilted at an angle of 53° relative to the plane described by the three pyrrole units (Figure 4).[70] Demetalation with TFA in chloroform gave the nonaromatic ketone **84** in good yield. This unusual oxidation product can also be obtained directly by reacting **44** with silver(I) acetate.



Scheme 9. Metalation of azuliporphyrins.

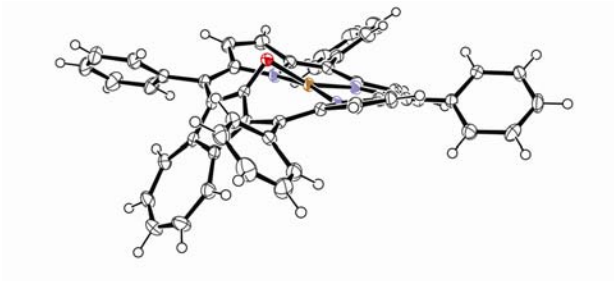


Figure 4. X-ray crystal structure of copper(II) complex **83**.[53]

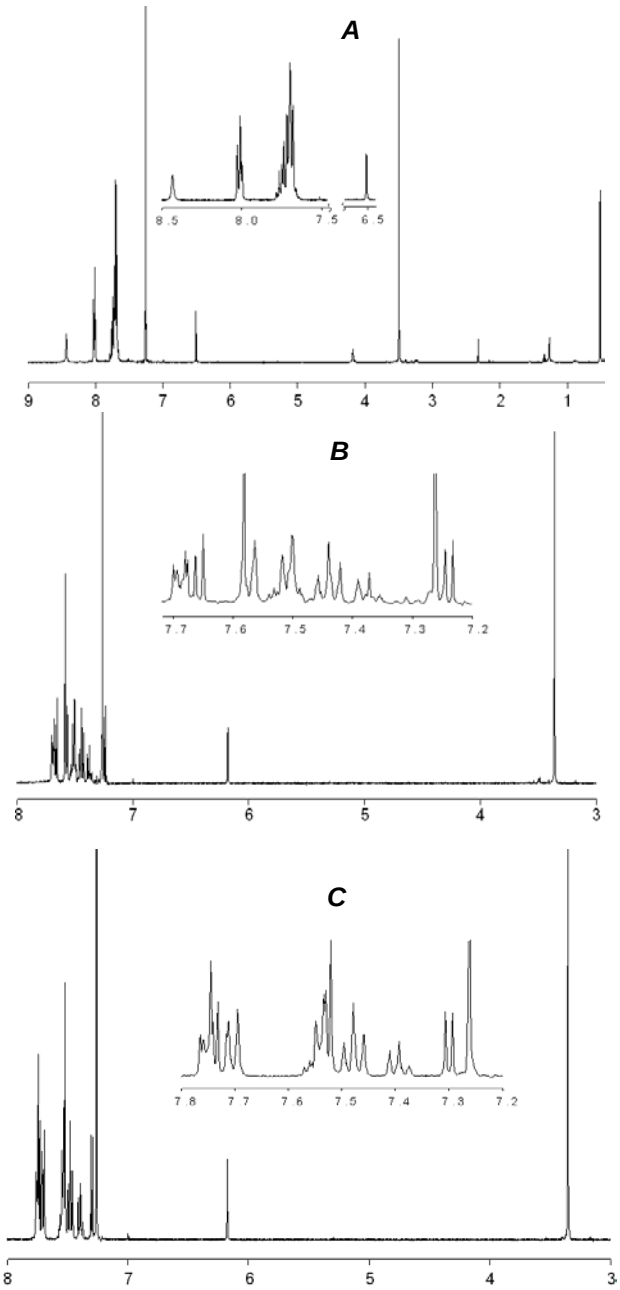
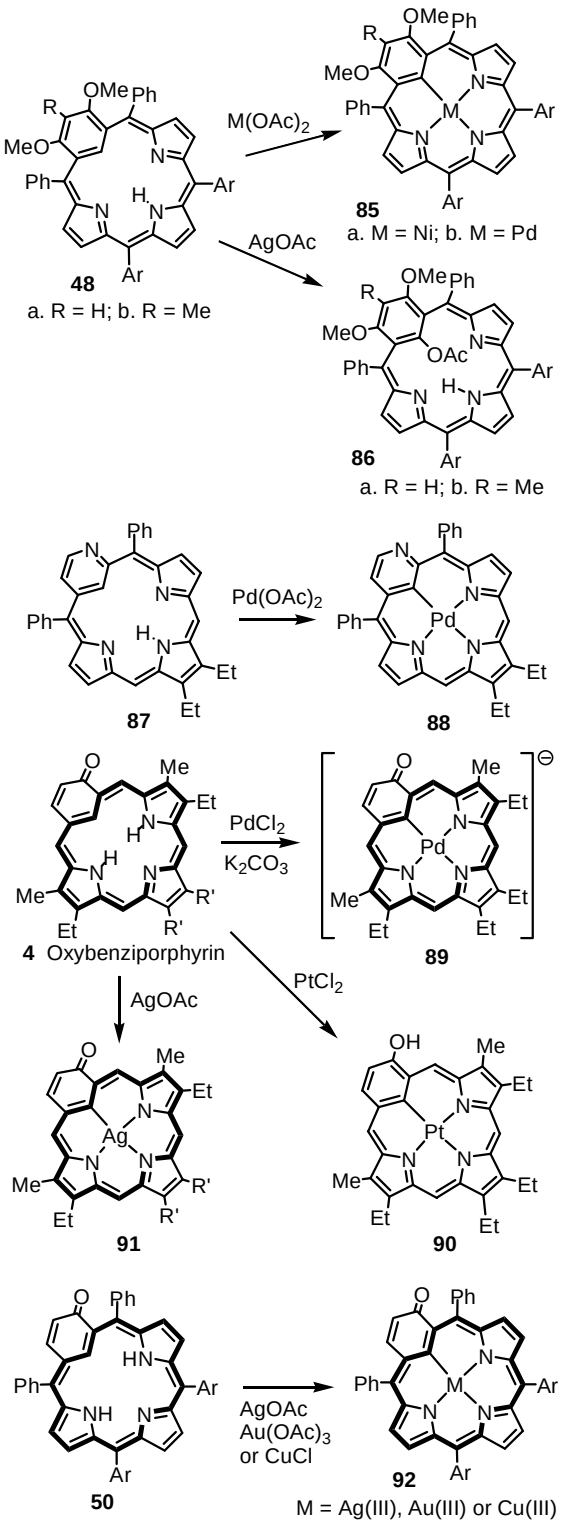


Figure 5. 400 MHz proton NMR spectra of tetraphenylbenziporphyrin derivatives in $CDCl_3$. All three compounds show some diatropic character even though these systems cannot be planar and have a cross-conjugated benzene subunit. *A* - Acetoxybenziporphyrin **86**. *B* - Nickel(II) complex **85** (M = Ni). *C* - Palladium(II) complex **85** (M = Pd).



Scheme 10. Metalation of benziporphyrins and oxybenziporphyrins.

Benziporphyrins allow for similar metalation reactions, and the tetraaryl substituted benziporphyrins have been shown to give Ni^{II}, Pd^{II}, Pt^{II} and other metallo-derivatives.[73] We have demonstrated (Scheme 10) that dimethoxybenziporphyrins **48** can also generate the nickel(II) and palladium(II) derivatives **85**, although reaction with silver(I) acetate gave the corresponding acetate **86**.[57,58] Interestingly, these 22-acetoxybenziporphyrin retain some diatropic character by NMR spectroscopy as do the Ni^{II} and Pd^{II} complexes (Figure 5).[58] Nevertheless, the nickel(II) complex of dimethoxy-tetraphenylbenziporphyrin **48** is quite nonplanar showing a highly twisted six-membered ring by X-ray crystallography (Figure 6).[57,58] An N-confused pyriporphyrin **87**, which can be considered to be a 2-azabenziporphyrin, was also shown to form a palladium(II) complex **88**.[40] Oxybenziporphyrin **4** was shown to form an anionic palladium(II) complex **89** that retains the keto-unit,[74,75] although the related platinum(II) complex appears to favor the phenolic form **90**.[71] Reaction of oxybenziporphyrins **4** with silver(I) acetate gave the silver(III) derivatives **91** in high yields.[41] Hence, oxybenziporphyrins resemble NCPs in that they can act as both dianionic and trianionic ligands. Tetraphenyl-oxybenziporphyrins **50** have been shown to generate copper(III), silver(III) and gold(III) complexes **91**, as well as a palladium(II) derivative.[59,60] Initial studies indicate that nickel(II) and platinum(II) complexes can be formed, but these have not been fully characterized.[60]

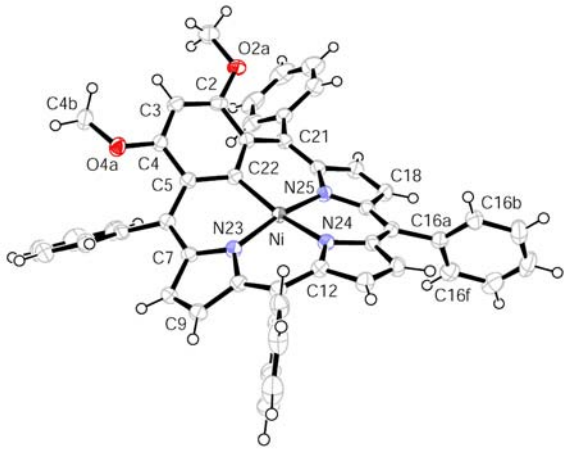
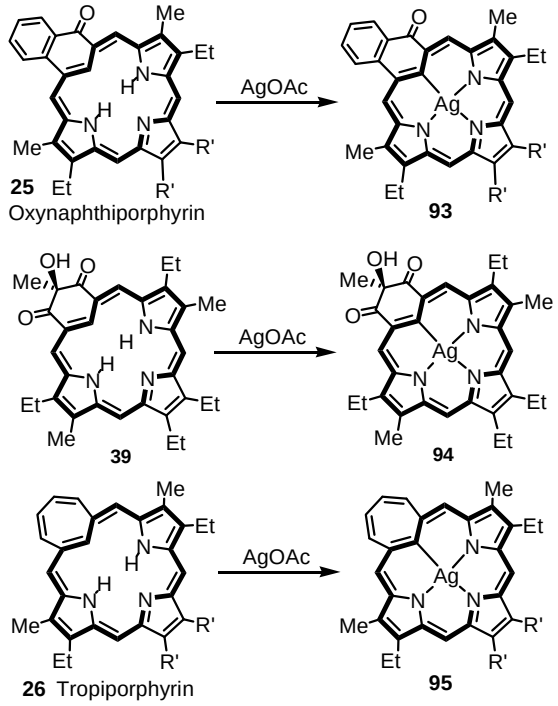


Figure 6. X-ray crystal structure of the nickel(II) complex of tetraphenyldimethoxybenziporphyrin **85**.[58]



Scheme 11. Silver(III) derivatives of carbaporphyrinoid systems.

Many carbaporphyrinoid systems have now been shown to form silver(III) derivatives (Scheme 11).[41] Oxynaphthiporphyrins **25** react with AgOAc to give silver(III) complexes **93**,[41] the 3-hydroxydiketone **39** similarly gives Ag^{III} complex **94**,[47] and tropiporphyrins **26** afford the Ag^{III} complexes **95**.[44] Although these silver(III) derivatives usually form under mild conditions, the tropiporphyrin silver(III) derivatives can only be generated at elevated temperatures. X-ray crystallography for one of these tropiporphyrin complexes showed that the macrocycle is highly distorted due to the strain factors introduced by the seven-membered ring (Figure 7).[42]

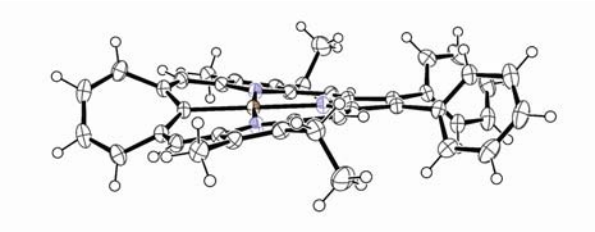
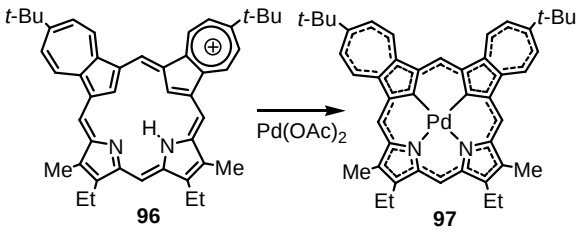


Figure 7. X-ray crystal structure of silver(III) tropiporphyrin **95** showing a high degree of distortion due to the presence of the cycloheptatriene subunit.[42]

The metalation of dicarbaporphyrinoids has not been properly explored as yet, but a diazuliporphyrin **96** (Scheme 12) was recently shown to form an unusual palladium(II) complex **97**.[76] This system has been characterized by X-ray crystallography and may well represent the first example of a whole series of dicarbaporphyrinoid derivatives of this type.



Scheme 12. Palladium(II) derivative of a diazuliporphyrin.

Conclusions

Efficient and versatile routes for the synthesis of carbaporphyrinoid systems have been developed. These porphyrin analogues range from highly aromatic systems to borderline aromatic or nonaromatic macrocycles, and the proton NMR data for these porphyrinoids provide significant insights into the nature of porphyrinoid aromaticity.[17-19] Many of these structures form stable organometallic derivatives under mild conditions. Benziporphyrins, azuliporphyrins, oxacarbaporphyrins and N-phenyl pyrazole-containing porphyrin analogues act as dianionic ligands, while benzocarbaporphyrins and tropiporphyrins are trianionic ligands that can stabilize metals in relatively high oxidation states (*e.g.* Ag^{III})[41] and may find applications as catalysts. Oxybenziporphyrins can act as trianionic or dianionic ligands, as can NCPs, and this allows the synthesis of stable Pd^{II}, Cu^{III}, Ag^{III} and Au^{III} derivatives.[59] In addition to discovering new organometallic systems, novel regioselective oxidation reactions have also been observed.[64] Oxidations of benzocarbaporphyrins with ferric chloride in the presence of alcohol solvents give carbaporphyrin ketals that have some promise as photosensitizers in PDT and are also being investigated as possible agents for treating *leishmaniasis*.[66] An initial example of a metalated dicarbaporphyrinoid system also suggests that further structural diversity in these unusual metalloporphyrin analogue systems will be possible.

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